UCRL- 92526, Revision 1
PREPRINT

THE EFFECT OF GAMMA IRRADIATION ON THE STRENGTH AND ELASTICITY OF CLIMAX STOCK AND WESTERLY GRANITES

W. B. Durham
J. M. Beiriger
M. Axelrod
S. Trettenero

This paper was prepared for submittal to
Nuclear and Chemical Waste Management

December 1985

Lawrence Livermore National Laboratory

THE EFFECT OF GAMMA IRRADIATION ON THE STRENGTH AND ELASTICITY OF CLIMAX STOCK AND WESTERLY GRANITES

ABSTRACT

We performed unconfined compression tests on 66 cylinders of Climax stock quartz monzonite (CSQM), half of which had received a gamma ray dose of 9 ± 1 MGy (0.9 Grad) and half of which had not. We performed similar tests on 30 cylinders of Westerly granite. The experiment on CSQM was capable of detecting a 7% change in the unconfined strength level of 200 MPa. The experiment showed no statistically significant change. Null results were also found for the effect of gamma irradiation upon Young's modulus and Poisson's ratio in CSQM and for that upon the unconfined compressional strength of Westerly granite. We thus conclude that gamma irradiation has no effect on the strengths of either CSQM or Westerly granite.

INTRODUCTION AND BACKGROUND

The concept of storage of high-level nuclear waste in underground rock formations was field tested in a recently concluded experiment called the Spent Fuel Test-Climax, or the SFT-C (1). The SFT-C was conducted 420 m underground in a body of quartz monzonite in the Climax Stock at the Nevada Test Site. One of the key objectives of the SFT-C is to determine what, if any, are the combined and separate effects of the radiation and heat from the nuclear waste on the host rock. This study is one of a number of laboratory projects aimed at determining the effects of radiation on the Climax stock quartz monzonite (CSQM).

From the standpoint of the SFT-C, the interest in the effect of irradiation on the mechanical and elastic properties of rock is not as strong as the interest in its effects on properties of more direct interest to the performance of the repository, such as fluid and thermal transport properties. However, a working assumption during the design of the SFT-C was that irradiation does not significantly affect the important properties of the rock. This report describes a series of laboratory experiments intended to confirm that assumption. In seeking confirmation of a negative result, we chose to research a property (unconfined compressive strength) which is more economically studied in the lab, owing to experimental simplicity, but which does bear close ties to fluid and thermal transport properties, primarily because of the key role played by microfractures in controlling all of the above mentioned properties (2). The argument we proposed was that if the mechanical properties of CSQM are affected, then there is a distinct possibility that the transport properties are also affected, so an investigation into the effects upon those properties should be considered.

The experiments were designed to avoid the ambiguous results of two earlier studies. The first study (3) involved compressive testing of 26 cylindrical samples of CSQM. Fourteen of the samples were subjected to a 13 MGy (1.3 Grad) dose of gamma irradiation from a ^{60}Co source over a 9-day period. The twelve remaining samples were held as control. All samples were then loaded compressively at a uniform rate, without benefit of confining pressure, until they failed. The irradiated group had a strength of 163.7 $\pm$ 35.2 MPa and the control group showed a strength of 204.4 $\pm$ 33.4 MPa. The Student's t statistic for the strength of these two groups is >0.99. Since great care had been taken to randomize the samples during preparation and during mechanical testing, the results indicated rather strongly that gamma irradation had a degrading effect on the unconfined compressive strength of CSQM.

The second study, which was intended to refine our understanding of this degrading effect, gave results so ambiguous that it was withheld from publication pending retesting (i.e., the present study). In three attempts to reproduce the results of the first study, each involving about 20 cylinders of CSQM, one experiment indicated a degrading effect, one gave no effect, and the third actually indicated a strengthening effect.

The emphasis in the earlier studies was on the ability of a comparative statistical analysis to defeat some rather large sources of experimental error, both random and systematic, which were present in the testing system or which were encountered in the course of testing. That strategy clearly failed. For the present study the emphasis was shifted to making as accurate and precise a measurement as reasonably possible. The testing apparatus was rebuilt, the number of samples was greatly increased, and samples of Westerly granite, a well-characterized, homogeneous granite, were included in the test matrix to provide a running calibration of the apparatus.

EXPERIMENTAL DESIGN

<u>Apparatus.</u> A new testing apparatus was built expressly for this experiment. It consisted of a 100-ton capacity reaction frame and a loading column specially designed for unconfined compression testing of our 25.4-mm-diamter by 63.5-mm-long cylindrical specimens. The loading column (Fig. 1) consisted of the sample, a 50-ton hydraulic ram for applying the load, redundant load cells above and below the sample, upper and lower platens between the load cells and sample, and wide, hardened steel caps between the load cells and frame (above) and ram (below). The upper platen was a hardened

steel plate whose secondary purpose was to prevent the upper load cell from bouncing about uncontrollably at sample failure. The lower platen was also of hardened steel and had a hemispherical seat of radius 12.7 mm to improve column alignment. Shims of aluminum foil 0.01 mm thick were placed between each sample end face and platen to minimize traction and damage caused by microscopic particles and asperities. Hardened steel caps 50 mm in diameter at either end of the column prevented indentation of the ram and loading frame.

Every effort was made to establish and maintain precise column alignment during the tests. The loading frame displayed symmetric elastic distortion for loads well in excess of those applied to the rock samples. Alignment fixtures were used to prevent any wandering with respect to the frame of the ram (below) and the 50-mm-diameter cap (above). In addition, a series of alignment fixtures, some of which were removable, provided a redundant definition of alignment and concentricity for all circularly symmetric column parts. Pre-test calibration exercises revealed that the diametrically opposed strain gauges on the sample (see below) provided a sensitive measure of column alignment and that the unaided eye viewing the slowly disappearing gap between the upper 50-mm cap and upper load cell was an excellent judge of parallelism (and hence alignment, given the use of centering fixtures). Non-parallelism could always be corrected by adjusting the slight amount of play in the two removable alignment fixtures.

Four load cells were used in the experiments, with two in use for any given test to provide an ongoing calibration check and a backup in the event of failure of one of the cells. All four load cells were recently calibrated at the Lawrence Livermore National Laboratory (LLNL). The same upper load cell was used throughout the tests. The lower cell was replaced periodically (both by design and because of accident) in order to check against possible cycling effects on the upper load cell.

The Westerly granite samples, whose mechanical properties are well established in the literature, served as an independent calibration of load and of the soundness of the apparatus.

Sample Preparation. The source of CSQM was 140-mm-diameter core from hole ISS-9 at the SFT-C, Area 15, Nevada Test Site. Of the 66 CSQM samples measured, all but six came from the 8.75- to 10.18-m interval along the core. The remaining six came from the 16.70- to 16.89-m interval. The Westerly granite samples were all taken from a single slab on hand at LLNL measuring approximately 600 mm x 175 mm x 100 mm. CSQM and Westerly granite provide a sharp petrographic contrast. The Westerly granite has a narrow range of grain sizes, from about 0.2 to 1.0 mm grain diameter, giving it a uniform appearance and a great popularity in rock mechanics research laboratories. Grain sizes in CSQM range from 0.5 to 1.5 mm for most of the rock, but it has a small volume (10-20%) of quartz phenocrysts up to 5 mm across and orthoclase feldspar phenocrysts often several centimeters across.

Test cylinders 25.4 mm in diameter were cored from the source rock. In order to perform the statistical blocking discussed below, samples were cored in pairs, that is, initial core lengths were > 130 mm and those cores were then cut in half to yield two samples. The slab of Westerly granite was without major flaws, whereas the 140-mm CSQM cores had a number of large fractures and joints, both healed and unhealed, which we attempted to avoid in coring.

Fifteen (double sample) cores, given numbers W01-W15, were taken from the Westerly granite, and each was usable. On the other hand, 55 cores, given numbers C01-C55, were taken from the CSQM but 22 of those were rejected because they either broke or contained fractures not fully healed. Even if enough core remained for a single sample, the entire core was rejected. The two samples cut from a single core were given the prefixes "a" and "b": thus samples C01a and C01b came from the same 130-mm length of 25.4-mm-diameter core.

The ends of the samples were then ground to a final length of 63.50 mm. The length variation among all 96 samples was ± 0.03 mm with the exception of samples W13b and W14a, both 63.38 mm in length. After grinding, sample end faces were parallel to 0.01 mm for all samples except C02b, C09b, and C42a, which had ends parallel to 0.02 mm. The cylindrical surfaces of the samples were left with an as-cored finish which was smooth to the touch but which was not otherwise specified.

Following preparation, the CSQM samples were examined by eye for the purpose of characterizing the size and distribution of orthoclase feldspar phenocrysts. The cylindrical faces of each CSQM sample were then photographed in color to provide a permanent record.

Prior to irradiation and experimentation, the samples were stored at laboratory room conditions. The CSQM and Westerly granite samples were stored in separate boxes.

<u>Sampling Strategy.</u> In our earlier tests on CSQM, the mean unconfined compressive strength (σ_u) was approximately 200 $\pm$ 30 MPa (1 std. dev.). Westerly granite has been found by Byerlee (4) to have σ_u = 230 $\pm$ 10 MPa. The high variability in σ_u for CSQM as compared to Westerly is probably caused by the extreme structural inhomogeneity of CSQM. It was our intention to reduce the variability in σ_u through both instrumental and statistical methods.

If there is some physical correlation between the "a" and "b" sections of a given 130-mm long core, as the scale of inhomogeneities in the CSQM suggests there might be, then the sensitivity of the experiment may be increased by a technique known as "blocking". In general, a block is a unit of experimental material within which the variation of some attribute is less than its variation between blocks. Treatment comparisons are then made within blocks rather than across blocks. The different blocks can be viewed as independent replications of the comparison. Since the "block size" in our experiments is two (the "a" and "b" portions of a 130-mm core), the method is also known as the method of "matched pairs". For each pair one section is exposed to a massive dose of gamma radiation while the other section acts as a control. For validity, the two sections must be treated identically in all other respects. Any radiation effect is detected by a comparison of σ_u between the members of a pair.

If the ultimate strengths of unirradiated "a" and "b" portions are independent, i.e. uncorrelated, then the matched pair design offers no advantage. However, if there is some correlation between members of a pair, then some reduction in variability necessarily results. At the extreme, if it could somehow be established that each member of a pair has exactly the same unirradiated σ_u, then exactly one sample pair would be sufficient to carry out the experiment.

<u>Sampling Size</u>. The sampling size (n) is the number of matched pairs as discussed above (meaning 2n short cores are tested). The following parameters uniquely determine n:

ξ = fractional change in σ_u caused by the radiation.

α = probability of a "false positive" i.e. the conclusion of a radiation effect when none in fact exists.

β = probability of a "false negative", i.e. the conclusion of no radiation effect when it does in fact exist.

s = standard deviation of σ_u

If each of these parameters is specified, then a unique sample size n may be determined for a given statistical test. We chose the following set of parameters for the reasons outlined in the following paragraph

$\xi = 0.1$
$\alpha = 0.05$
$\beta = 0.1$
$s = 25$ MPa

With these values n = 35 if Student's t-test is used. The value of s = 25 MPa is a conservative estimate based on our previous tests of CSQM. The value of $\xi = 0.1$ implies a change of 20 MPa induced by radiation. Such an experiment would have a 90% chance of detecting at least this change in σ_u at a significance level $\alpha = 0.05$. Such an experiment would have a false positive rate of 5% and a false negative rate of 10%. This assumes no reduction in variance from improved instrumentation or blocking.

Randomization. Except for the deliberate handling of samples in matched pairs, the order of irradiation and testing of each sample was randomized with respect to its location in the source rock. The 33 CSQM pairs were listed in random order using a standard randomizer on the LLNL computer system. (Specifically, the command "RANDO" in the computer routine "MATHSY" was used. MATHSY is described in Reference 5.) The same thing was done for the 15 Westerly pairs. The two lists were then folded together into a master list (Table 1) which preserved the order within the CSQM and Westerly groups and which alternated 2 CSQM, 1 Westerly, 2 CSQM, 1 Westerly, and so on. The samples were then taken in order from the master list for irradiation and also for mechanical testing.

In order to avoid effects of possible systematic differences between the "a" and "b" portions of the pairs, those pairs were scrambled twice. First, to assign members to gamma or control, a line of random digits was chosen by a series of coin flips from the book A Million Random Digits (Reference 6; the line chosen was on p. 369, line 31, cumulative line number 18430). Taking the cores in numerical order, with the Westerly list following the CSQM list, the "a" member was assigned to the irradiation group if the associated digit on that line was odd; it was assigned to the control group if the number was even. Secondly, the "a" and "b" order of mechanical testing was randomized, using the same radomizer on the LLNL computer system as mentioned above. The second scrambling was necessary in order to decouple a pair's irradiation treatment and testing order.

EXPERIMENTAL PROCEDURE

Gamma Irradiation. The gamma irradiation procedure duplicated that used in our earlier published study (3). Irradiation was carried out in the ^{60}Co irradiation pool at the LLNL Standards and Calibrations Laboratory. Details of the characteristics of the source are given by Elliott (7). The source is made up of 72 ^{60}Co rods 190 mm long arranged in a circle 110 mm in diameter. The source lies at the bottom of a 6-m-deep pool of deionized water. The size of the sample chamber in the gamma cell allowed irradiation of up to 10 samples at a time, in the arrangement shown in Fig. 2a. Samples were in direct contact with the water in the cell.

Primary gamma ray energies of the ^{60}Co source and of the spent fuel canisters used in the SFT-C are both of the order of 1 MeV, where the dominant energy transfer mechanism is expected to involve Compton interactions. Therefore, no direct enhancement of damage per rad is expected at higher dose rates. However, if a time-dependent recovery of damage occurs, laboratory scaling to shorter times would tend to make damage in the laboratory samples higher for a given absorbed dose, in keeping with the conservative design of the test. Page (8) has found that at least one gamma ray-induced change, in thermoluminescence, can be reversed over time. Time was considered to be an important variable in the tests and to minimize possible effects of time-dependent recovery, the delay between irradiation and mechanical testing was kept brief.

The irradiation time was $0.950 \pm 0.002 \times 10^6$ s (11 days ± 30 minutes). To compensate for the non-uniformity of gamma ray intensity within the ^{60}Co sample cell and for the slight attenuation of gamma rays in rock (the mean free path of 1 MeV gamma rays is roughly 60 mm), the samples were repositioned and rotated according to a preplanned schedule (Fig. 2b) three times during irradiation. Every effort was made to handle control samples in the same manner as the corresponding irradiated samples, except to avoid their exposure to gamma rays. They were placed and arranged in the same type of open canister as were the irradiated samples, but instead of being lowered into the pool, the control samples were placed alongside the pool in a stainless steel bucket filled with water from the pool. The water was dumped back into the pool and replaced with new pool water each time the irradiated samples were removed for rotation.

The ^{60}Co cell was carefully calibrated immediately following the irradiation of the final group of rocks. Using the same canister and sample holder used for the rocks, six pieces of radiochromic film distributed around the volume otherwise occupied by the rocks showed a variation in intensity from 8.6 to 10.5 Gy/s with a mean within the volume of about 9.7 Gy/s (970 rad/s). Measurements of film density were based on comparison to National Bureau of Standards calibrated film and are believed accurate to 8%.

Accounting for a few per cent attenuation of gamma radiation in rock, then, over the 11-day exposure, the rocks received a total dose of 9 ± 1 MGy (0.9 Grad). The maximum dose to rock over the 3-year duration of the SFT-C was roughly 1.5 MGy (9).

Following irradiation, irradiated and control samples were wiped dry and placed back together in the same box. After at least 2 days of drying in laboratory air, strain gauges were applied. As before, two biaxial rosettes with longitudinal and circumferential components were placed opposite one another on the cylindrical surface of each rock. The rosettes were attached with epoxy directly to the rock surface. In a departure from earlier procedures, gauges with like orientations were wired independently (rather than in series) in order to monitor (rather than cancel the effects of) sample bending. Sample orientations were monitored through all aspects of handling, so we were able to mount all strain gauges at the same azimuth with respect to the original source of material.

Mechanical Testing. The test sample and pieces of aluminum foil (the only pieces which were replaced from run to run) were aligned and fixed in place using the two removable alignment jigs (Fig. 1). With the alignment jigs still in place, the operator ran the ram up to near closure of the column, then checked for and corrected any minute misalignment (as described under "Apparatus"). With the column satisfactorily aligned, the operator used the ram to load the sample to 2 ± 0.5 MPa. At that point, the operator stopped the ram and removed the two removable alignment jigs, effectively removing all mechanical support from the cylindrical surface of the sample.

Loading of the test specimen was controlled manually. Feedback to the operator was a printout on the computer display of the running time at every strain increment of 2×10^{-5}. The operator loaded the sample rapidly to a level near 100 MPa and thereafter controlled the strain rate to 1.5 to $4 \times 10^{-6}\ s^{-1}$ until the rock failed. The unusual and varied nature of inelastic deformation in the rock in the moments just prior to ultimate failure occasionally caused the macroscopic strain rate to move outside this range.

Because of the distinctive darkening taken on by irradiated samples, the person who assembled a sample into the apparatus could not help but know whether the sample was irradiated or control. In order to avoid operator biasing, unintentional or otherwise, a second operator was called upon to perform the sample assembly. Unfortunately, it was possible to mask only half the samples in this manner. No guarantee could be made that the first operator not see the scattered remains of a fractured sample and thereby know whether or not it had been irradiated. Since the samples were tested in pairs, the first operator would then know the treatment of the next sample. Therefore, the second operator was called upon to assemble only the first sample of each pair.

Data Acquisition and Analysis. Experimental data consisted of voltage outputs from two load cells, the resistance change of four strain gauges on the rock, the voltage of the single power supply used by the load cells and bridge completion device, and time, measured by the internal clock of the computer. All signals except time were read with a Hewlett-Packard 3497A data acquisition system which passed the information to an LSI-11 computer. The computer wrote all data to hard disc, and printed running information on a line printer and on the display. The data acquisition system was calibrated by the manufacturer just prior to its use in this study.

The quantities derived from the data files were similar to those calculated in the earlier work (3): the maximum stress applied (σ_u), maximum Young's modulus at longitudinal strain above 0.1% (E), and Poisson's ratio at 0.1% longitudinal strain (ν). Additionally, we generated diagnostic plots for qualitative examination of potential trouble: longitudinal vs. longitudinal strain and circumferential vs. circumferential strain from the opposing gauges on each rock, both diagnostic of sample bending, and hence column misalignment; and upper load vs. lower load, diagnostic of problems with the load cells.

RESULTS

A total of 96 rock cylinders were loaded unconfined to ultimate brittle failure. The results of the tests are given in Table 1. One pair of CSQM cores (#41) was used in pilot tests so it could not be used in the statistical analysis. Four of the CSQM cores, each from a different pair were accidentally loaded too fast. Thus, of the 66 CSQM samples, 60 individual runs (29 irradiated, 31 control) are usable and only 28 matched pairs exist for the analysis. Experimental difficulties (involving the computer rather than the mechanical hardware) eliminated only one of the Westerly runs from consideration, so of the original 30 samples, 29 individual runs (14 irradiated, 15 control) or 14 pairs were usable in the analysis.

DISCUSSION

<u>Effect of Gamma Irradiation</u>. As regards the effect of gamma irradiation on unconfined compression strength, the t statistic for 28 pairs of CSQM is - 0.864 (Table 2a), meaning that the difference in σ_u between control and irradiated is not significantly different from zero. Thus, an effect of gamma irradiation on σ_u was not detected. Modifying the design parameters under "Sampling Size" to those actually encounted (n = 28, s = 22 MPa), the experiment had a 90% chance of detecting a 14 MPa change in σ_u at the 5% significance level, with a two-sided t-test.

A measure of the validity of the t-test in this experiment is given in Figure 3 which is a probability plot of the ultimate strength for all CSQM cores. A straight line indicates conformity to the Gaussian distribution. We note some non-Gaussian behavior, in that the distribution is skewed to the left as indicated by the change in slope below 200 MPa. There is no apparent pattern in the appearance of control or irradiated points. The t test is known to have robustness of validity for this degree of departure from the Gaussian distribution (10).

Similarly, for Westerly granite, 14 pairs give a t statistic of -0.572 (Table 2b), again indicating no radiation effect. Irradiation has also not measurably affected Young's modulus (Table 3) or Poisson's ratio (Table 4) in CSQM.

Blocking. The lack of an effect of gamma irradiation has rendered the point moot for this study, but from a statistical standpoint and with the possibility in mind of using CSQM in a future experiment, it is worthwhile determining whether or not the blocking technique (i.e. the use of matched pairs) has increased the sensitivity of the experiment.

Blocking will have been a useful technique in the case where the breaking strengths of the "a" and "b" sections are correlated. The estimated correlation coefficient for σ_u of associated "a" and "b" sections, calculated from Tables 1 and 2a, is $\rho = 0.408$ based on $n = 28$. Applying Fisher's Z transformation (11, p. 419-420) to ρ we get

$$Z = 1/2 \ln \frac{1 + \rho}{1 - \rho} = 0.433$$

This statistic is known to be approximately Gaussian with variance

$= \frac{1}{(n-1)} + \frac{2}{(n-1)^2}$ for small ρ. For $n = 28$ we get a variance for Z of 0.040, or a standard deviation of 0.199. Our observed value of $Z = 0.433$ is thus 2.17 standard deviations, a strong indication that there is correlation between the "a" and "b" portions. Formally the hypothesis $\rho = 0$ can be rejected at a two-sided significance level of 3%.

It should be noted that this analysis is sensitive to outliers which tend to enlarge the calculated correlation coefficient. A nonparametric analysis should be applied to confirm this result.

Apparatus Calibration. The results of the Westerly granite samples which show $\sigma_u = 200 \pm 5$ MPa (Table 2b), indicate that the apparatus had excellent reproducibility over the course of 96 runs. Also, the standard deviation of < 20 MPa for CSQM (Table 2a) is a distinct improvement over the values near 30 MPa produced by the apparatus used in the previous irradiation studies (3). The magnitude of σ_u for Westerly does not agree with Byerlee's (4) value of 230 ± 10 MPa. The redundant load cells in our system invariably agreed within a very few MPa, so the cause of the disagreement with Byerlee lies with some difference in the details of the different measurement systems, or with the Westerly granite itself.

It is clear that CSQM has a considerably more poorly defined σ_u than does Westerly, at least for samples of the size tested here. An important cause of this is certainly the structural heterogeneity of CSQM. This heterogeneity is described and discussed by Beiriger and Durham (12) and is consistent with the apparent correlation between rock pairs discussed above.

Comparison to Earlier Work. Why, then, did the earlier experiment described under "Introduction and Background" give such a strong indication that gamma irradiation does affect σ_u in CSQM? A similar question was pondered at length in the unpublished second study of this series. There is, and was, an unsatisfying predicament. Within the realm of physics seem to lie only two explanations: random chance and differing sample populations. The probability of producing the results of the first experiment given a material with no gamma irradiation effect is very low, given the strong t statistic of >0.99. The possibility of sampling differences arises because material for the first study came from a point in the quartz monzonite body about 50 m horizontally distant from the workings at SFT-C. While the CSQM is notoriously heterogeneous on scales up to several meters, heterogeneity on the 50 m scale has not been researched.

Whatever the explanation, the results of the present study that gamma irradiation does not measurably affect σ_u in CSQM must predominate, owing to the larger number of samples tested here and to the demonstrably better reproducibility of the testing apparatus.

CONCLUSION

We compared the elastic moduli and unconfined compressive strength of two kinds of Climax Stock quartz monzonite samples: those that had been given a gamma ray dosage of 9 $\pm$ 1 MGy (0.9 Grad) and those which were unirradiated. The experiment was designed to have a 90% chance of detecting at least a 10% difference in strength at a significance level of 0.05. No effect was detected. The experimental design was conservative with respect to the variances actually encountered; in fact the experiment established that any effect of irradiation on strength is probably less than 7%.

Similarly, we detected no effect of irradiation on Young's modulus or Poisson's ratio in CSQM. Identical tests conducted on Westerly granite, primarily to assure good system calibration, detected no effect of gamma irradiation on its unconfined compressive strength.

A technique of sample selection by matched pairs, called "blocking," indicated there exists in CSQM a significant spatial correlation at the 50-100-mm distance level in one or more of the physical properties which cause unconfined compressive failure.

ACKNOWLEDGMENTS

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48. This study was conducted as part of the Nevada Nuclear Waste Storage Investigations of the U.S. Department of Energy.

5384x/0032x

REFERENCES

(1) Ramspott, L. D., Ballou, L. B., Carlson, R. C., Montan, D. N., Butkovich, T. R., Duncan, J. E., Patrick, W. C., Wilder, D. G., Brough, W. T., and Mayr, M. C, Technical concept for a test of geologic storage of spent reactor fuel in the climax granite at the Nevada Test Site. UCRL-52796, Lawrence Livermore National Laboratory, Livermore, CA, (1979).

(2) Kranz, R. L., Microcracks in rocks: A review. Tectonophys. 100: 449-480, (1983).

(3) Durham, W. B., The effect of gamma irradiation on the strength of Climax Stock quartz monzonite. UCRL-87475, Lawrence Livermore National Laboratory, Livermore, CA, (1982).

(4) Byerlee, J. D., Reply. J. Geophys. Res. 74: 5349-5350, (1969).

(5) Peterson, G., MATHSY Manual. UCID 18875, Lawrence Livermore National Laboratory, Livermore, CA, (1984).

(6) RAND Corporation, A Million Random Digits. The Free Press, (1955).

(7) Elliott, J. H., Tour of the Standards and Calibrations Laboratory. UCRL-52537, Lawrence Livermore National Laboratory, Livermore, CA, (1978).

(8) Page, L., Effect of radiation from spent fuel canisters on rock. Memorandum WI:LP-79-36, Lawrence Livermore National Laboratory, Livermore, CA, (November 13, 1979).

(9) Wilcox, T. P. and Van Konynenburg, R. A., Radiation dose calculations for geologic media around spent fuel emplacement holes in the Climax granite, Nevada Test Site. UCRL-53159, Lawrence Livermore National Laboratory, Livermore, CA, (1981).

(10) Box, G. E. P., Hunter, W. G., and Hunter, J. S., Statistics for Experimentors. Wiley, (1978).

(11) Kendall, M. G., The Advanced Theory of Statistics. 4th edition, McMillian, (1978).

(12) Beiriger, J. M., and Durham, W. B., SEM studies of stressed and irradiated Climax Stock quartz monzonite. UCID-20052, Lawrence Livermore National Laboratory, Livermore, CA, (1984).

FIGURE CAPTIONS

Figure 1. The loading apparatus. Shown is a sample being aligned in the column for testing. For scale, the sample is 63.5 mm long. At the base of the column is the ram used to load the sample. A large cap covers the top end of the ram and has a hole through the center into which fits very precisely the lower load cell (the dog-bone-shaped piece of steel below the sample). Between the lower load cell and sample is the swivel platen. The male hemispherical portion of the platen sits against the sample. Above the sample is a flat platen (with the word "FRONT" scribed on it in the figure) and upper load cell. At the top of the column is a fixed centering fixture for the top load cell. Alignment of all parts of the column is achieved by the two removable centering fixtures which surround the lower load cell and bottom end of the sample, and upper load cell and top end of the sample. Each of the removable fixtures is in two pieces, with only one piece of each visible in the figure.

Figure 2. Positioning and rotation of test samples during gamma irradiation. (a) Arrangement of 10 samples within gamma cell. The ^{60}Co gamma ray source surrounds the samples. (b) The rotation schedule for a given pair (one above and one below) of samples shown in (a). The samples are interchanged, flipped over, and rotated. The orientation mark is simply an ink marking; it is shown here as a dashed line when it is on the far side of the sample.

Figure 3. Probability plot for breaking strengths of all the CSQM samples. "g" indicates a gamma-irradiated sample and "c" represents a control sample. The fact that the points lie along a line that is nearly straight is support for the validity of the t-test in detecting an effect of irradiation.

TABLE 1. Randomized Irradiation and Testing Sequence

Sequence	*Rock	Core #	Portion Irradiated	Portion Tested First	Irradiation Dates
1	CSQM	C41	b	a	
2	CSQM	C08	b	a	
3	WEST	W09	b	a	3/19/84
4	CSQM	C54	a	a	
5	CSQM	C24	b	a	to 3/30/84
6	WEST	W11	b	b	
7	CSQM	C09	a	b	
8	CSQM	C28	a	a	
9	WEST	W06	b	b	
10	CSQM	C44	b	b	
11	CSQM	C14	b	a	
12	WEST	W07	b	a	
13	CSQM	C13	a	b	4/2/84
14	CSQM	C01	a	b	
15	WEST	W12	a	b	to 4/13/84
16	CSQM	C31	b	a	
17	CSQM	C18	b	b	
18	WEST	W03	a	a	
19	CSQM	C06	b	b	
20	CSQM	C45	b	a	
21	WEST	W08	a	a	
22	CSQM	C17	a	a	4/16/84
23	CSQM	C11	b	b	
24	WEST	W13	b	b	to 4/27/84
25	CSQM	C26	b	b	
26	CSQM	C30	b	b	
27	WEST	W10	b	b	
28	CSQM	C42	b	a	
29	CSQM	C02	b	a	
30	WEST	W02	a	a	
31	CSQM	C36	a	a	4/30/84
32	CSQM	C07	a	b	
33	WEST	W15	b	b	to 5/11/84
34	CSQM	C32	a	a	
35	CSQM	C35	a	b	
36	WEST	W04	a	b	
37	CSQM	C10	b	a	
38	CSQM	C22	b	b	

39	WEST	W14	a	a	
40	CSQM	C23	b	a	
41	CSQM	C12	a	b	5/14/84
42	WEST	W01	a	a	
43	CSQM	C46	a	b	to 5/25/84
44	CSQM	C53	a	b	
45	WEST	W05	b	b	
46	CSQM	C49	a	b	
47	CSQM	C29	b	a	
48	CSQM	C19	b	a	

*"CSQM" = Climax Stock Quartz Monzonite
"WEST" = Westerly Granite

TABLE 2a. Ultimate Strength vs. Gamma Irradiation for CSQM

Core #	Control	Gamma	Difference
C01	227.64 MPa	205.31	22.32
C02	197.52	207.01	-9.43
C06	212.52	218.62	-6.11
C07	195.02	187.62	7.39
C08	165.54	170.46	-4.92
C09	215.11	NA	NA
C10	157.32	221.37	-64.04
C11	178.44	213.27	-34.83
C12	191.64	144.68	46.97
C13	217.64	213.24	4.39
C14	222.76	221.58	1.17
C17	205.70	220.19	-14.50
C18	237.95	211.53	26.42
C19	208	203.6	4.40
C22	214.14	227.89	-13.75
C23	179.36	197.84	-18.48
C24	NA*	200.15	NA
C26	213.67	NA	NA
C28	221.52	221.47	0.05
C29	208.40	219.50	-11.19
C30	201.04	203.54	-2.50
C31	180.78	225.41	-44.63
C32	206.81	222.44	-15.63
C35	219.10	215.43	3.68
C36	215.21	204.04	11.17
C42	218.20	189.42	28.79
C44	170.56	NA	NA
C45	200.66	220.86	-20.20
C46	200.91	201.81	-0.90
C49	208.14	199.77	8.37
C53	200.25	201.84	-1.59
C54	203.15	206.59	-3.45
Mean	203.05	206.78	-3.61
Std. dev.	18.65	17.57	22.08
Student's t			-0.864

*NA = Data not acquired or not acceptable

Table 2b. Ultimate Strength vs. Gamma Irradiation for Westerly Granite

Core #	Control	Gamma	Difference
W01	204.81 MPa	203.15	1.66
W02	193.91	203.59	-9.68
W03	201.36	193.35	8.01
W04	200.40	N/A	N/A
W05	199.93	195.32	4.60
W06	201.68	206.02	-4.34
W07	204.44	196.51	7.93
W08	198.09	199.16	-1.066
W09	203.91	194.19	9.71
W10	203.93	207.77	-3.83
W11	195.56	208.60	-13.03
W12	204.65	204.15	0.49
W13	200.33	205.85	-5.53
W14	191.00	197.20	-6.20
W15	195.49	198.89	-3.40
Mean	199.97	200.98	-1.05
Std. dev.	4.32	5.21	6.85
Student's t			-.572

Table 3. Young's Modulus vs. Gamma Irradiation for CSQM

Core #	Control	Gamma	Difference
C01	68604 MPa	71245	-2642
C02	70510	69523	987
C06	70640	59183	11457
C07	49811	62441	-12630
C08	88427	62720	25708
C09	64104	NA	NA
C10	38900	61577	-22676
C11	62196	56799	5398
C12	72728	69143	3585
C13	63126	61992	1135
C14	65581	50949	14632
C17	64744	65495	-751
C18	59733	64312	-4579
C19	NA	61280	NA
C22	58557	58224	333
C23	64169	55614	8554
C24	NA	56907	NA
C26	58163	NA	NA
C28	68477	67686	791
C29	NA	63905	NA
C30	51098	55509	-4412
C31	24969	73412	-48443
C32	NA	56507	NA
C35	51326	68453	-17127
C36	66942	44103	22839
C42	62260	49097	13163
C44	45032	NA	NA
C45	47959	46933	1026
C46	58193	63809	-5616
C49	69913	55773	14140
C53	58768	62168	-3400
C54	78891	NA	NA
Mean	68051	60527	61
Std.dev.	12532	7266	15358
Student's t			.019

Table 4. Poisson's Ratio vs. Gamma Irradiation for CSQM

Core #	Control	Gamma	Difference
C01	0.19	0.27	-0.08
C02	0.22	0.15	0.07
C06	0.20	0.19	0.02
C07	0.23	0.18	0.05
C08	0.41	0.26	0.15
C09	0.25	NA	NA
C10	0.27	0.30	-0.02
C11	0.18	0.25	-0.07
C12	0.42	0.23	0.19
C13	0.18	0.49	-0.31
C14	0.24	0.19	0.05
C17	0.29	0.13	0.16
C18	0.23	0.11	0.12
C19	NA	0.23	NA
C22	0.27	0.21	0.06
C23	0.14	0.31	-0.17
C24	NA	0.23	NA
C26	0.16	NA	NA
C28	0.15	0.32	-0.17
C29	NA	0.17	NA
C30	0.27	0.32	-0.05
C31	0.20	0.44	-0.23
C32	NA	0.24	NA
C35	0.16	NA	NA
C36	0.25	0.25	0.00
C42	0.20	0.11	0.09
C44	0.12	NA	NA
C45	0.12	0.19	0.06
C46	0.23	0.25	0.02
C49	0.32	0.25	0.07
C53	0.18	0.11	0.07
C54	0.63	NA	NA
Mean	0.24	0.24	0.00
Std. dev.	0.11	0.09	0.13
Student's t			-0.16

5384x/0119x

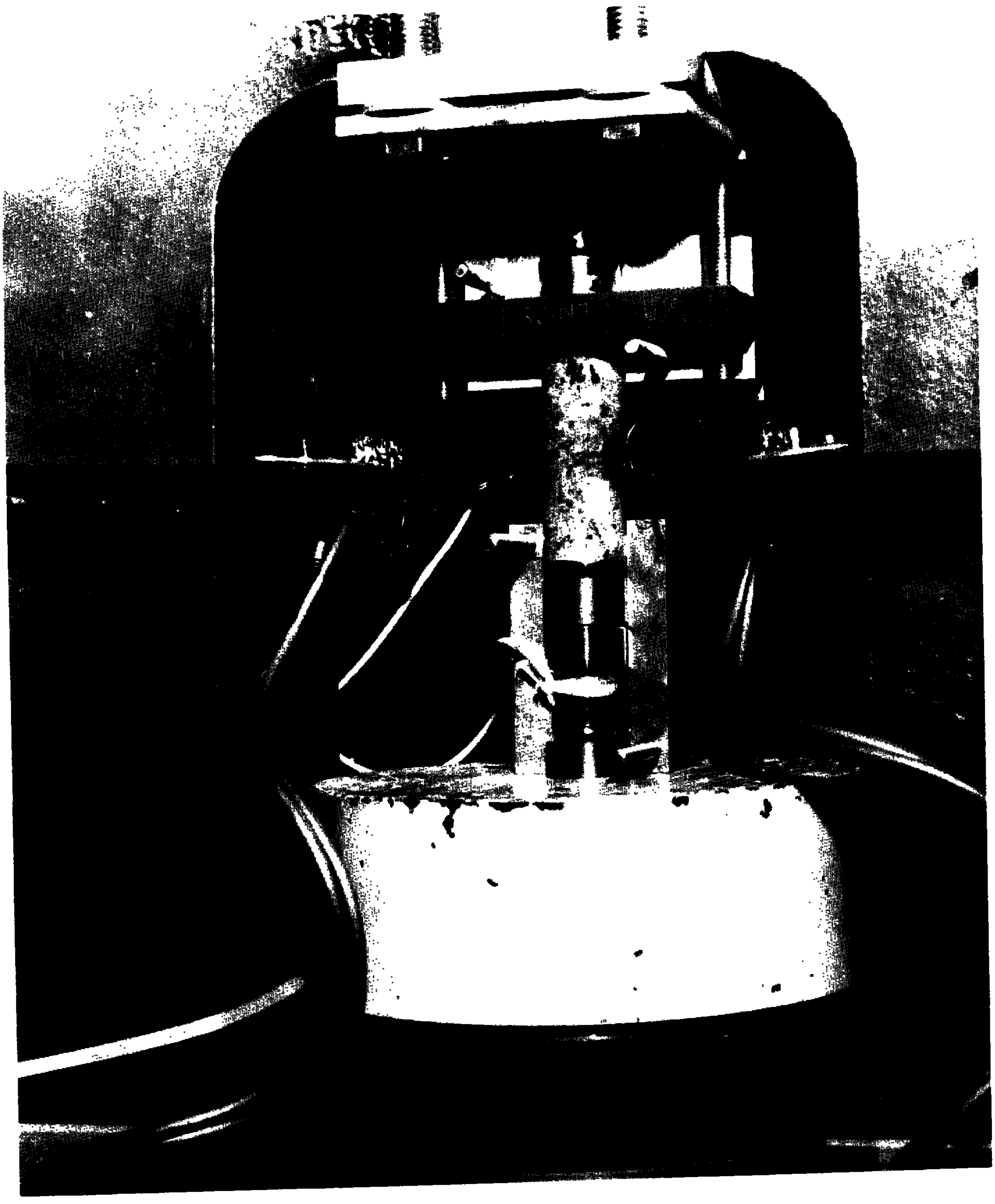


Fig. 1

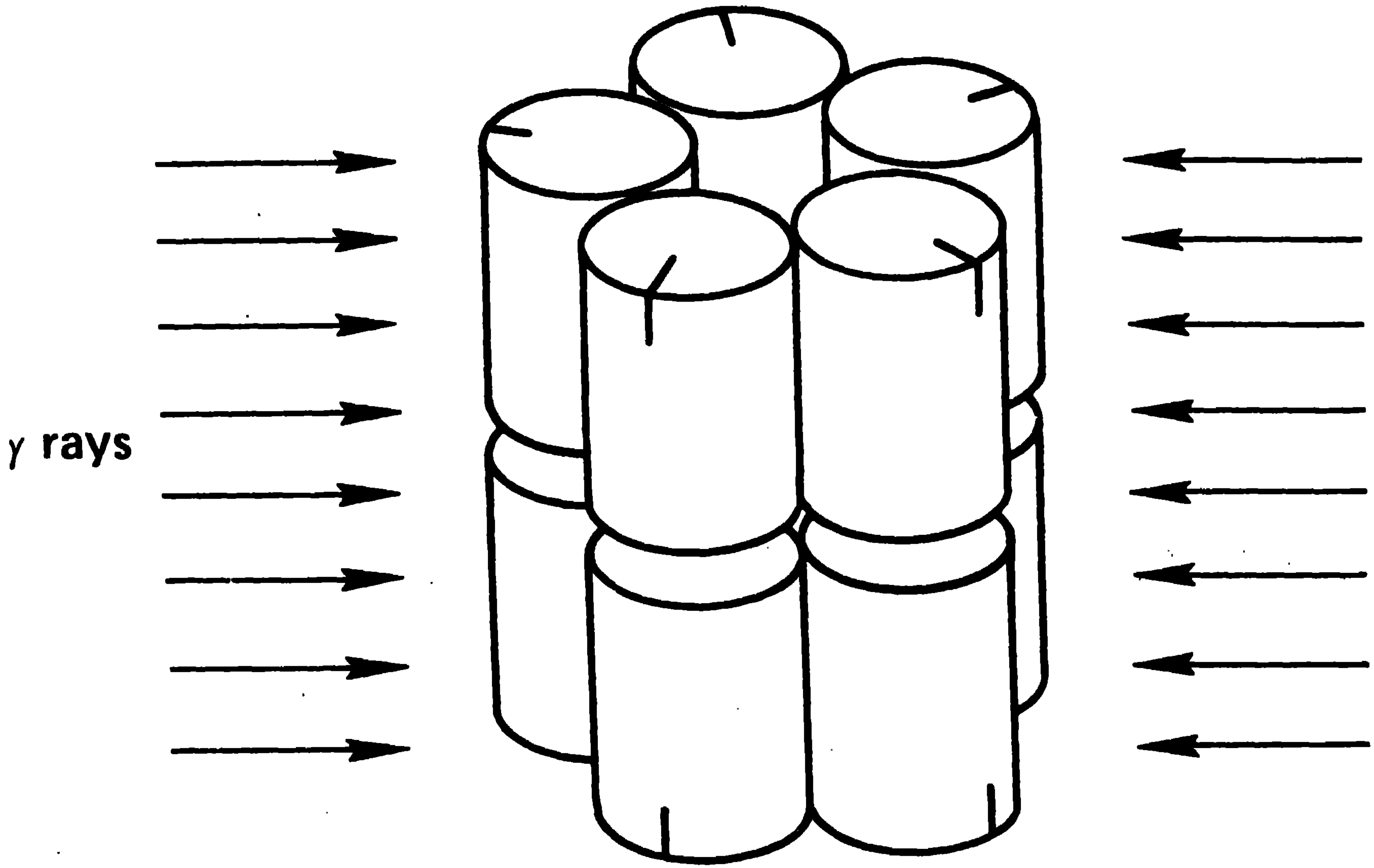


Fig. 2a

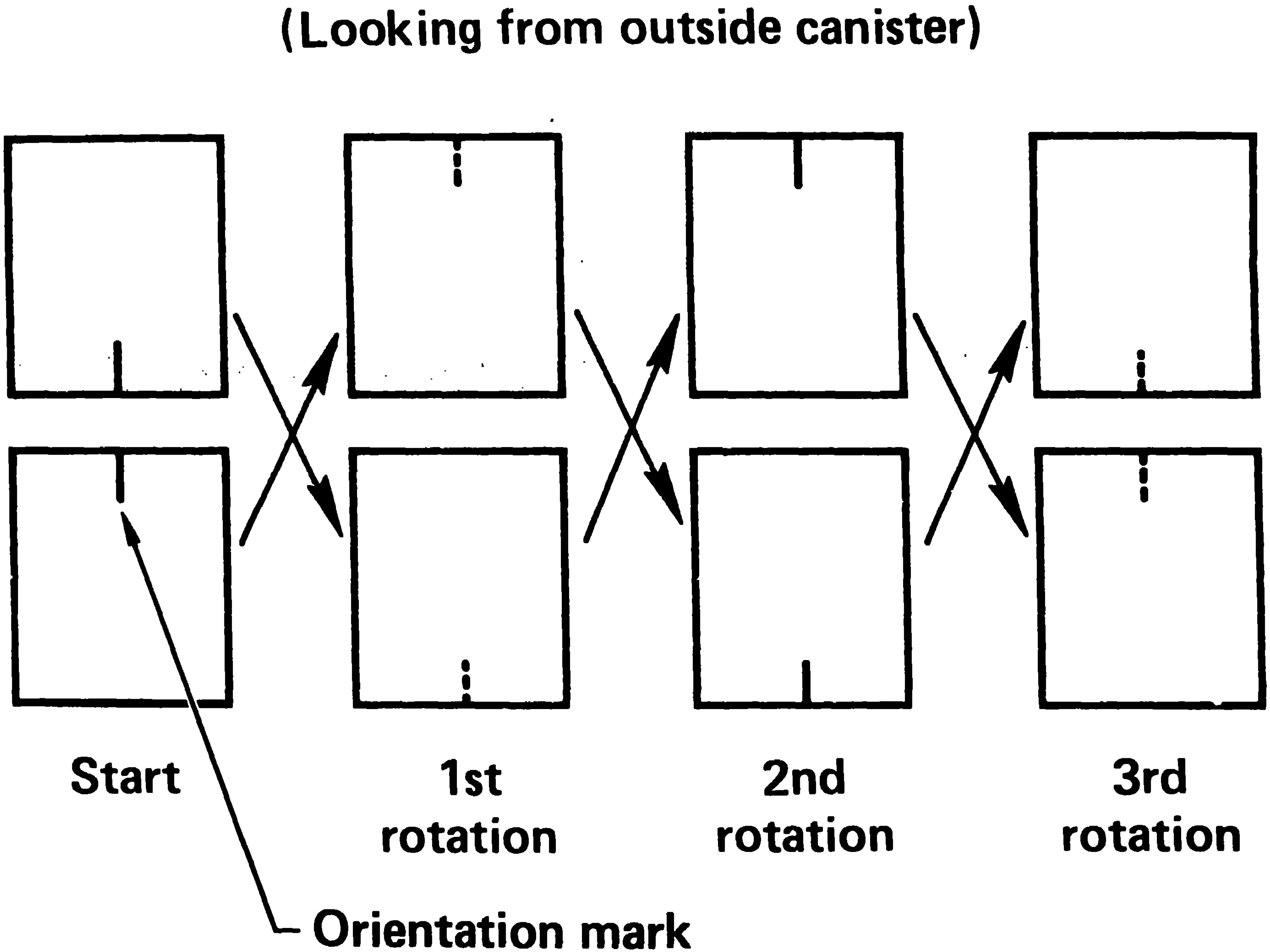
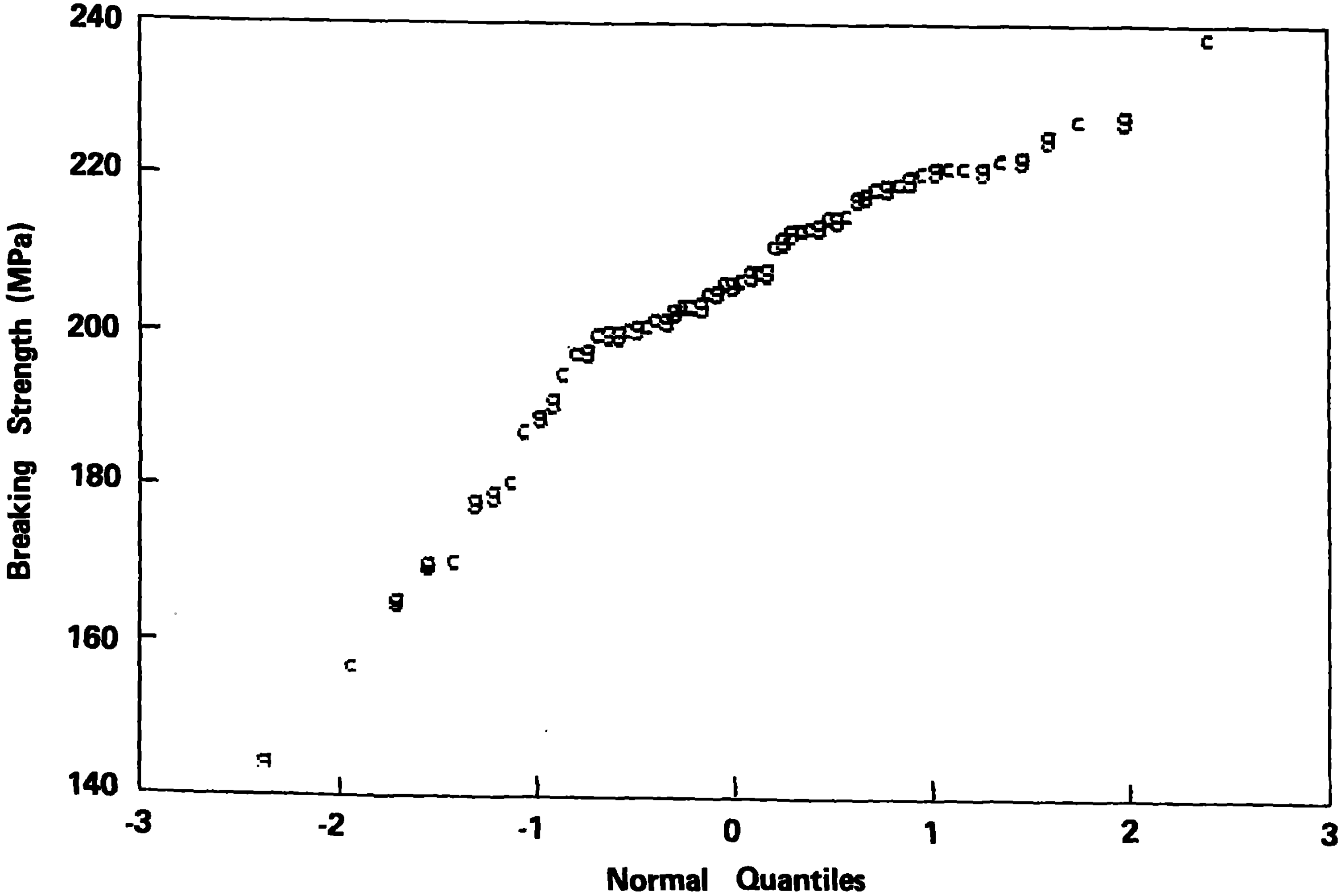

(Looking from outside canister)
Start
1st rotation
2nd rotation
3rd rotation
Orientation mark

Fig. 2b

Fig. 3



Breaking Strength (MPa)
240
220
200
180
160
140
-3
-2
-1
0
1
2
3
Normal Quantiles